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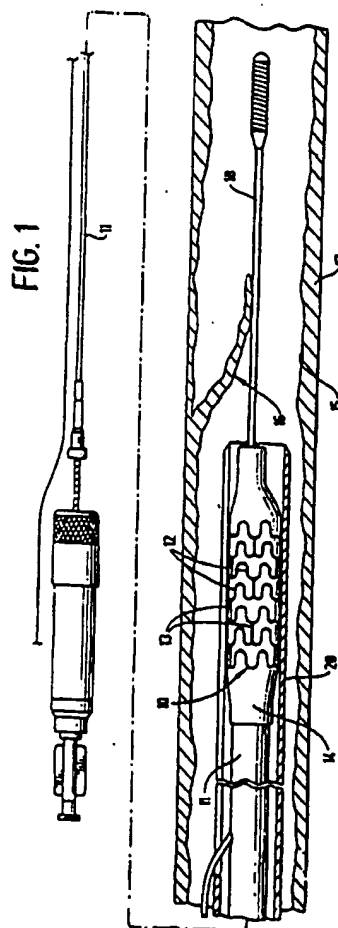
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(54) **Method and apparatus for direct laser cutting of metal stents**

(57) An improved expandable stent (10) for implantation in a body lumen, such as an artery, and an improved method for making it from a single length of tubing. The stent (10) consists of a plurality of radially expandable cut cylindrical elements (12) generally aligned on a common axis and interconnected by one or more interconnective elements (13), the elements (12) having a rectangular cross-section from cut-to-cut. The individual radially expandable cylindrical elements (12) are disposed in an undulating pattern. The stent (10) is manufactured by direct laser cutting from a single metal tube using a finely focused laser beam passing through a co-axial gas jet structure to impinge on the working surface of the tube as the linear and rotary velocity of the tube is precisely controlled.



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## Description

BACKGROUND OF THE INVENTION

5 This invention relates generally to improvements in the manufacture of expandable metal stents and, more particularly, to new and improved methods and apparatus for direct laser cutting of metal stents and providing stents of enhanced structural quality.

Stents are expandable endoprosthesis devices which are adapted to be implanted into a body lumen of a patient, such as a blood vessel, to maintain the patency of the vessel. These devices typically are used in the treatment of  
10 atherosclerotic stenosis in blood vessels and the like.

In the medical arts, stents generally are tubular-shaped devices which function to hold open a segment of a blood vessel or other anatomical lumen. Stents particularly are suitable for use to support and hold back a dissected arterial lining which can occlude the fluid passageway.

Various means have been provided to deliver and implant stents. One method frequently described for delivering  
15 a stent to a desired intraluminal location includes mounting the expandable stent on an expandable member, such as a balloon, provided on the distal end of an intravascular catheter, advancing the catheter to the desired location within the body lumen of a patient, inflating the balloon on the catheter to expand the stent into a permanently expanded condition and then deflating the balloon and removing the catheter.

One example of a particularly useful expandable stent is a stent which is relatively flexible along its longitudinal  
20 axis to facilitate delivery through tortuous body lumens, but which is stiff and stable enough radially when in an expanded condition so as to maintain the patency of a body lumen such as an artery when implanted within the lumen. Such a desirable stent typically includes a plurality of radially expandable cylindrical elements which are relatively independent in their ability to expand and to flex relative to one another. The individual radially expandable cylindrical elements of the stent are precisely dimensioned so as to be longitudinally shorter than their own diameters. Interconnecting elements or struts extending between adjacent cylindrical elements provide increased stability and a preferable position  
25 to prevent warping of the stent when it is expanded. The resulting stent structure is a series of radially expandable cylindrical elements which are spaced closely enough longitudinally so that small dissections in the wall of a body lumen may be pressed back into position against the luminal wall, but not so closely as to compromise the longitudinal flexibility of the stent. The individual cylindrical elements may rotate slightly relative to adjacent cylindrical elements without significant deformation, cumulatively resulting in a stent which is flexible along its length and about its longitudinal axis, but which is still very stiff in the radial direction in order to resist collapse.

The aforescribed stents generally have a precisely laid out circumferential undulating pattern, e.g., serpentine. The transverse cross-section of the undulating component of the cylindrical element is relatively small and preferably  
35 has an aspect ratio of about two to one (2:1) or about one-half to one (0.5/1). A one to one (1:1) aspect ratio has been found to be particularly suitable. The open reticulated structure of the stent allows for the perfusion of blood over a large portion of the arterial wall, which can improve the healing and repair of a damaged arterial lining.

The radial expansion of the expandable cylinder deforms the undulating pattern similar to changes in a waveform which result from decreasing the amplitude and the frequency. Preferably, the undulating patterns of the individual  
40 cylindrical structures are in phase with each other in order to prevent the contraction of the stent along its length when it is expanded. The cylindrical structures of the stent are plastically deformed when expanded so that the stent will remain in the expanded condition and, therefore, the structures must be sufficiently rigid when expanded to prevent collapse during deployment of the stent. Upon expansion of the stent, portions of the undulating pattern will tip outwardly resulting in projecting members on the outer surface of the expanded stent. These projecting members tip radially outwardly from the outer surface of the stent and embed into the vessel wall and help secure the expanded stent so  
45 that it does not move once it is implanted.

The elongated elements which interconnect adjacent cylindrical elements should have a precisely defined transverse cross-section similar to the transverse dimensions of the undulating components of the expandable cylindrical elements. The interconnecting elements may be formed as a unitary structure with the expandable cylindrical elements from the same intermediate product, such as a tubular element, or they may be formed independently and connected  
50 by suitable means, such as by welding or by mechanically securing the ends of the interconnecting elements to the ends of the expandable cylindrical elements. Preferably, all of the interconnecting elements of a stent are joined at either the peaks or the valleys of the undulating structure of the cylindrical elements which form the stent. In this manner, there is no shortening of the stent upon expansion.

The number and location of elements interconnecting adjacent cylindrical elements can be varied in order to develop  
55 the desired longitudinal flexibility in the stent structure both in the unexpanded, as well as the expanded condition. These properties are important to minimize alteration of the natural physiology of the body lumen into which the stent is implanted and to maintain the compliance of the body lumen which is internally supported by the stent. Generally, the greater the longitudinal flexibility of the stent, the more easily and the more safely it can be delivered to the implan-

tation site.

It will be apparent from the foregoing that conventional stents are very high-precision, relatively fragile devices and, ideally, the most desirable metal stents incorporate a fine precision structure cut from a very small diameter, thin-walled cylindrical tube. In this regard, it is extremely important to make precisely-dimensioned, smooth, narrow cuts in the stainless tubes in extremely fine geometries without damaging the narrow struts that make up the stent structure. While the various cutting processes, including chemical etching, heretofore have been used to form such expandable metal stents and have been adequate, improvements have been sought to provide stents of enhanced structural quality in terms of resolution, reliability and yield.

Accordingly, those concerned with the development, manufacture and use of metal stents long have recognized the need for the improved manufacturing processes for such stents.

#### SUMMARY OF THE INVENTION

Briefly, certain embodiments of the present invention provide a new and improved method and apparatus for direct laser cutting of metal stents enabling greater precision, reliability, structural integrity and overall quality, without burrs, slag or other imperfections that otherwise might hamper stent integrity and performance.

A first embodiment of the present invention provides an improved system for producing metal stents with a fine precision structure, cut from a small diameter, thin-walled, cylindrical tube. The tubes typically are made of stainless steel and are fixtured under a laser and positioned utilizing a computer numerical control (CNC) fixture to generate a very intricate and precise pattern. Due to the thin-wall and the small geometry of the stent pattern, it is necessary to have very precise control of the laser, its power level, the focus spot size, and the positioning of the laser cutting path.

In a presently preferred embodiment of the invention, in order to minimize the heat input, to avoid thermal distortion, uncontrolled burn out of the metal, and metallurgical damage due to excessive heat, a Q-switched Nd:YAG (neodymium: yttrium aluminum garnet) laser that is frequency doubled to produce a green beam at 532 nanometers is used. Q-switching produces very short pulses (< 100 nanoseconds) of high peak powers (kilowatts), low energy per pulse ( $\leq 3$  millijoules), at high pulse rates (up to 40 kilohertz). The frequency doubling of the beam from 1.06 microns to 0.532 microns allows the beam to be focused to a spot size that is 2 times smaller than is a non-frequency doubled beam and, therefore, the power density is increased by a factor of four. With all of these parameters, it is possible to make smooth, narrow cuts in the stainless tubes in very fine geometries without damaging the narrow struts that comprise the stent structure.

In addition to the laser and the CNC positioning equipment, the optical delivery system used in the practice of the present invention includes a beam expander to increase the laser beam diameter; a circular polarizer to eliminate polarization effects in metal cutting; provisions for a spatial filter; a binocular viewing head and focusing lens; and a coaxial gas jet that provides for the introduction of a gas stream that surrounds the focused beam and is directed along the beam axis. The coaxial gas jet nozzle is centered around the focused beam with approximately 0.25 millimeters (0.01 inch) between the tip of the nozzle and the tubing. The jet is pressurized with oxygen at 3.87 cm-Hg (20 lbs/in<sup>2</sup>) and is directed at the tube with the focused laser beam exiting the tip of the nozzle. The oxygen reacts with the metal to assist in the cutting process very similar to what occurs with oxyacetylene cutting. The focused laser beam acts as an ignition source and controls the reaction of the oxygen with the metal. In this manner, it is possible to cut the material with a very fine kerf with precision. In order to prevent burning by the beam and/or molten slag on the far wall of the tube inside diameter, a stainless steel mandrel is placed inside the tube and is allowed to roll on the bottom of the tube as the pattern is cut. This mandrel acts as a beam/debris block, protecting the far wall inside diameter.

The cutting process utilizing oxygen with the finely focused green beam results in a very narrow kerf (approximately 0.013 millimeters (0.0005 inch) with the molten slag resolidifying along the cut. This traps the cut-out scrap of the pattern and which requires further processing to remove. In order to remove the slag debris from the cut allowing the scrap to be removed from the remaining stent pattern, it is desirable to soak the cut tube in a solution of hydrochloric acid (HCL) for a selected time and temperature. Before it is soaked, the tube is placed in a bath of alcohol and water solution and ultrasonically cleaned for approximately 1 minute to remove the loose debris left from the cutting operation. After soaking, the tube then is ultrasonically cleaned in the heated HCL for a period of time dependent upon the wall thickness. To prevent cracking or breaking of the struts attached to the material left at the two ends of the stent pattern as a result of harmonic oscillations induced by the ultrasonic cleaner, a mandrel is placed down the center of the tube during the cleaning and scrap removal process. At completion of this process, the stent structures are rinsed in water. They are then ready for electropolishing.

Hence, the new and improved method and apparatus for direct laser cutting of metal stents, embodying the present invention, make accurate, reliable, high resolution, expandable stents with patterns having smooth, narrow cuts and very fine geometries.

The above and other objects and advantages of this invention will be apparent from the following more detailed description when taken in conjunction with the accompanying drawings of exemplary embodiments.

DESCRIPTION OF THE DRAWINGS

FIGURE 1 is an elevational view, partially in section, of a stent embodying features of the invention which is mounted on a delivery catheter and disposed within a damaged artery;

FIG. 2 is an elevational view, partially in section, similar to that shown in FIG. 1 wherein the stent is expanded within a damaged artery, pressing the damaged lining against the arterial wall;

FIG. 3 is an elevational view, partially in section showing the expanded stent within the artery after withdrawal of the delivery catheter;

FIG. 4 is a perspective view of a stent embodying the invention in an unexpanded state, with one end of the stent being shown in an exploded view to illustrate the details thereof;

FIG. 5 is a plan view of a flattened section of a stent which illustrates the undulating pattern of the stent shown in FIG. 4;

FIG. 5a is a sectional view taken along the line 5a-5a in FIG. 5;

FIG. 6 is a schematic representation of equipment for selectively cutting the tubing in the manufacture of stents;

FIG. 7 is an elevational view of a system for cutting an appropriate pattern by laser in a metal tube to form a stent;

FIG. 8 is a plan view of the laser head and optical delivery subsystem for the laser cutting system shown in FIG. 7;

FIG. 9 is an elevational view of a coaxial gas jet, rotary collet, tube support and beam blocking apparatus for use in the system of FIG. 7;

FIG. 10 is a sectional view taken along the line 10-10 in FIG. 9;

FIG. 11 is an elevational and schematic drawing of laser beam diameter versus spot size and depth of focus; and

FIG. 12 is an elevational and schematic drawing of focal length versus spot size and depth of focus.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings, and particularly to FIG. 1 thereof, there is shown a stent 10 which is mounted onto a delivery catheter 11. The stent 10 is a high-precision patterned tubular device. The stent 10 typically comprises a plurality of radially expanded cylindrical elements 12 disposed generally coaxially and interconnected by elements 13 disposed between adjacent cylindrical elements. The delivery catheter 11 has an expandable portion or balloon 14 for expanding of the stent 10 within an artery 15. The artery 15, as shown in FIG. 1 has a dissected lining 16 which has occluded a portion of the arterial passageway.

The typical delivery catheter 11 onto which the stent 10 is mounted, is essentially the same as a conventional balloon dilatation catheter for angioplasty procedures. The balloon 14 may be formed of suitable materials such as polyethylene, polyethylene terephthalate, polyvinyl chloride, nylon and ionomers such as that manufactured under the tradename "SURLYN" by the Polymer Products Division of the E. I. Du Pont de Nemours Company. Other polymers also may be used. In order for the stent 10 to remain in place on the balloon 14 during delivery to the site of the damage within the artery 15, the stent 10 is compressed onto the balloon. A retractable protective delivery sleeve 20, as described in copending application Serial No. 07/647,464 filed on April 25, 1990 and entitled STENT DELIVERY SYSTEM, may be provided to further insure that the stent stays in place on the expandable portion of the delivery catheter 11 and to prevent abrasion of the body lumen by the open surface of the stent 20 during delivery to the desired arterial location. Other means for securing the stent 10 onto the balloon 14 also may be used, such as providing collars or ridges on the ends of the working portion, *i.e.*, the cylindrical portion, of the balloon.

Each radially expandable cylindrical element 12 of the stent 10 may be independently expanded. Therefore, the balloon 14 may be provided with an inflated shape other than cylindrical, *e.g.*, tapered, to facilitate implantation of the stent 10 in a variety of body lumen shapes.

The delivery of the stent 10 is accomplished in the following manner. The stent 10 is first mounted onto the inflatable balloon 14 on the distal extremity of the delivery catheter 11. The balloon 14 is slightly inflated to secure the stent 10

onto the exterior of the balloon. The catheter-stent assembly is introduced to the vasculature of the patient in a conventional Seldinger technique through a guiding catheter (not shown). A guidewire 18 is disposed across the damaged arterial section having the detached or dissected lining 16 and then the catheter-stent assembly is advanced over a guidewire 18 within the artery 15 until the stent 10 is directly under the detached lining 16. The balloon 14 of the catheter is expanded, expanding the stent 10 against the artery 15, which is illustrated in FIG. 2. While not shown in the drawing, the artery 15 is preferably expanded slightly by the expansion of the stent 10 to seat or otherwise fix the stent 10 to prevent movement. In some circumstances during the treatment of stenotic portions of an artery, the artery may have to be expanded considerably in order to facilitate passage of blood or other fluid therethrough.

The stent 10 serves to hold open the artery 15 after the catheter 11 is withdrawn, as illustrated by FIG. 3. Due to the formation of the stent 10 from an elongated tubular member, the undulating component of the cylindrical elements of the stent 10 is relatively flat in transverse cross-section, so that when the stent is expanded, the cylindrical elements are pressed into the wall of the artery 15 and as a result do not interfere with the blood flow through the artery 15. The cylindrical elements 12 of the stent 10 which are pressed into the wall of the artery 15 eventually will be covered with endothelial cell growth which further minimizes blood flow interference. The undulating portion of the cylindrical sections 12 provide good tacking characteristics to prevent stent movement within the artery. Further, the closely spaced cylindrical elements 12 at regular intervals provide uniform support for the wall of the artery 15, and consequently are well adapted to tack up and hold in place small flaps or dissections in the wall of the artery 15, as illustrated in FIGS. 2 and 3.

FIG. 4 is an enlarged perspective view of the stent 10 shown in FIG. 1 with one end of the stent shown in an exploded view to illustrate in greater detail the placement of interconnecting elements 13 between adjacent radially-expandable cylindrical elements 12. Each pair of the interconnecting elements 13 on one side of a cylindrical element 12 preferably are placed to achieve maximum flexibility for a stent. In the embodiment shown in FIG. 4, the stent 10 has three interconnecting elements 13 between adjacent radially expandable cylindrical elements 12 which are 120° apart. Each pair of interconnecting elements 13 on one side of a cylindrical element 12 are offset radially 60° from the pair on the other side of the cylindrical element. The alternation of the interconnecting elements results in a stent which is longitudinally flexible in essentially all directions. Various configurations for the placement of interconnecting elements are possible. However, as previously mentioned, all of the interconnecting elements of an individual stent should be secured to either the peaks or valleys of the undulating structural elements in order to prevent shortening of the stent during the expansion.

The number of undulations may also be varied to accommodate placement of interconnecting elements 13, e.g., at the peaks of the undulations or along the sides of the undulations as shown in FIG. 5.

As best observed in FIGS. 4 and 5, cylindrical elements 12 are in the form of a serpentine pattern. As previously mentioned, each cylindrical element 12 is connected by interconnecting elements 13. The serpentine pattern is made up of a plurality of U-shaped members 31, W-shaped members 32, and Y-shaped members 33, each having a different radius so that expansion forces are more evenly distributed over the various members.

The afordescribed illustrative stent 10 and similar stent structures can be made in many ways. However, the preferred method of making the stent is to cut a thin-walled tubular member, such as stainless steel tubing, to remove portions of the tubing in the desired pattern for the stent, leaving relatively untouched the portions of the metallic tubing which are to form the stent. In accordance with the invention, it is preferred to cut the tubing in the desired pattern by means of a machine-controlled laser as illustrated schematically in FIG. 6.

The tubing may be made of suitable biocompatible material such as stainless steel. The stainless steel tube may be Alloy type: 316L SS, Special Chemistry per ASTM F138-92 or ASTM F139-92 grade 2; Special Chemistry of type 316L per ASTM F138-92 or ASTM F139-92 Stainless Steel for Surgical Implants in weight percent.

Carbon (C)	0.03% max.
Manganese (Mn)	2.00% max.
Phosphorous (P)	0.025% max.
Sulphur (S)	0.010% max.
Silicon (Si)	0.75% max.
Chromium (Cr)	17.00 - 19.00%
Nickel (Ni)	13.00 - 15.50%
Molybdenum (Mo)	2.00 - 3.00%
Nitrogen (N)	0.10% max.
Copper (Cu)	0.50% max.
Iron (Fe)	Balance

The stent diameter is very small, so the tubing from which it is made necessarily must also have a small diameter.

Typically the stent has an outer diameter on the order of about 1.52 millimeters (0.06 inch) in the unexpanded condition, the same outer diameter of the tubing from which it is made, and can be expanded to an outer diameter of 2.54 millimeters (0.1 inch) or more. The wall thickness of the tubing is about 0.076 millimeters (0.003 inch).

Referring to FIG. 6, the tubing 21 is put in a fixture having rotatable collets 22 of a machine-controlled apparatus 23 for positioning the tubing 21 relative to a laser 24. According to machine-encoded instructions, the tubing 21 is rotated and moved longitudinally relative to the laser 24 which also is machine-controlled. The laser selectively removes the material from the tubing by ablation and a pattern is cut into the tube. The tube therefore is cut into the discrete pattern of the finished stent.

The process of cutting a pattern for the stent into the tubing is automated except for the loading and unloading of the length of tubing. Referring again to FIG. 6 loading may be accomplished for example, using a CNC-opposing collet fixture 22 for axial rotation of the length of tubing, in conjunction with a CNC X/Y table 25 to move the length of tubing axially relative to a machine-controlled laser as described. The entire space between collets can be patterned using the CO<sub>2</sub> laser set-up of the foregoing example. The program for control of the apparatus is dependent on the particular configuration used and the pattern to be ablated in the coating.

Referring now to FIGS. 7-10 of the drawings, there is shown a process and apparatus, in accordance with the invention, for producing metal stents with a fine precision structure cut from a small diameter thin-walled cylindrical tube. Cutting a fine structure (0.09 millimeter (0.0035 inch) web width) requires minimal heat input and the ability to manipulate the tube with precision. It also is necessary to support the tube yet not allow the stent structure to distort during the cutting operation. In order to successfully achieve the desired end results, the entire system must be configured very carefully. The tubes are made of stainless steel with an outside diameter of 1.524 millimeters to 1.676 millimeters (0.060 inch to 0.066 inch) and a wall thickness of 0.051 millimeters to 0.102 millimeters (0.002 inch to 0.004 inch). These tubes are fixtured under a laser and positioned using a CNC to generate a very intricate and precise pattern. Due to the thin wall and the small geometry of the stent pattern (0.09 millimeter (0.0035 inch) typical web width), it is necessary to have very precise control of the laser, its power level, the focused spot size, and the precise positioning of the laser cutting path.

In order to minimize the heat input into the stent structure, which prevents thermal distortion, uncontrolled burn out of the metal, and metallurgical damage due to excessive heat, and thereby produce a smooth debris-free cut, a Q-switched Nd:YAG laser typically available from Quantronix of Hauppauge, New York is used, that is frequency-doubled to produce a green beam at 532 nanometers. Q-switching produces very short pulses (<100 nanoseconds) of high peak powers (kilowatts), low energy per pulse ( $\leq 3$  millijoules), at high pulse rates (up to 40 kilohertz). The frequency doubling of the beam from 1.06 microns to 0.532 microns allows the beam to be focused to a spot size that is 2 times smaller than a non-frequency doubled beam, therefore increasing the power density by a factor of 4 times. With all of these parameters, it is possible to make smooth, narrow cuts in the stainless tubes in very fine geometries without damaging the narrow struts that make up the stent structure. Hence, the system described makes it possible to adjust the laser parameters to cut narrow kerf width which will minimize the heat input into the material.

The positioning of the tubular structure requires the use of precision CNC equipment such as that manufactured and sold by the Anorad Corporation. In addition, a unique rotary mechanism has been provided that allows the computer program to be written as if the pattern were being cut from a flat sheet. This allows both circular and linear interpolation to be used in the programming. Because the finished structure of the stent is very small, a precision drive mechanism is required that supports and drives both ends of the tubular structure as it is cut. Since both ends are driven, they must be aligned and precisely synchronized, otherwise the stent structure would twist and distort as it is being cut. A suitable computer program for controlling the CNC equipment is enclosed herewith as Appendix A.

The optical system which expands the original laser beam, delivers the beam through a viewing head and focuses the beam onto the surface of the tube, incorporates a coaxial gas jet and nozzle that helps to remove debris from the kerf and cools the region where the beam interacts with the material as the beam cuts and vaporizes the metal. It also is necessary to block the beam as it cuts through the top surface of the tube and to prevent the beam, along with the molten metal and debris from the cut, from impinging on the opposite surface of the tube.

In addition to the laser and the CNC positioning equipment, the optical delivery system includes a beam expander to increase the laser beam diameter, a circular polarizer, typically in the form of a quarter wave plate, to eliminate polarization effects in metal cutting, provisions for a spatial filter, a binocular viewing head and focusing lens, and a coaxial gas jet that provides for the introduction of a gas stream that surrounds the focused beam and is directed along the beam axis. The coaxial gas jet nozzle (0.457 millimeter (0.018 inch) inner diameter (I.D.)) is centered around the focused beam with approximately 0.254 millimeter (0.010 inch) between the tip of the nozzle and the tubing. The jet is pressurized with oxygen at 3.87 cm-Hg (20 lbs/in<sup>2</sup>) and is directed at the tube with the focused laser beam exiting the tip of the nozzle (0.457 millimeter (0.018 inch) diameter). The oxygen reacts with the metal to assist in the cutting process very similar to the reaction that takes place during oxyacetylene cutting. The focused laser beam acts as an ignition source and controls the reaction of the oxygen with the metal. In this manner, it is possible to cut the material with a very fine kerf with precision. In order to prevent burning by the beam and/or molten slag on the far wall of the

tube inner diameter (I.D.) a stainless steel mandrel (approximately 0.864 millimeter (0.034 inch) diameter) is placed inside the tube and is allowed to roll on the bottom of the tube as the pattern is cut. This acts as a beam/debris block protecting the far wall I.D.

Alternatively, this debris collection can be accomplished by inserting a second tube, inside the stent tube which has an opening to trap the excess energy in the beam that is transmitted through the kerf as well as the debris that is ejected from the laser-cut kerf. A vacuum or positive pressure can be placed in this shielding tube to remove the collected debris.

Another technique that could be used to remove the debris from the kerf and to cool the surrounding material would be to use the inner beam blocking tube as an internal gas jet. By sealing one end of the tube, making a small hole in the side, and placing it directly under the focused laser beam, gas pressure could be applied creating a small jet that would force the debris out of the laser-cut kerf from the inside out. This would eliminate any debris from forming or collecting on the inside of the stent structure. It would place all the debris on the outside. With the use of special protective coatings, the resultant debris then easily could be removed.

In most cases, the gas utilized in the jets may be reactive or non-reactive (inert). In the case of reactive gas, oxygen or compressed air is used. Compressed air is used in this application because it offers more control of the material removed and reduces the thermal effects of the material itself. Inert gas such as argon, helium, or nitrogen can be used to eliminate any oxidation of the cut material. The result is a cut edge with no oxidation, but there usually is a tail of molten material that collects along the exit side of the gas jet which must be removed mechanically or chemically after the cutting operation.

The cutting process utilizing oxygen with the finely focused green beam results in a very narrow kerf (approximately 0.0127 millimeter (0.0005 inch)) with the molten slag resolidifying along the cut. This traps the cut-out scrap of the pattern which requires further processing to remove. In order to remove the slag debris from the cut allowing the scrap to be removed from the remaining stent pattern, it is necessary to soak the cut tube in a solution of HCL for approximately 8 minutes at a temperature of approximately 55° C. Before it is soaked, the tube is placed in a bath of alcohol and water solution and ultrasonically is cleaned for approximately 1 minute, to remove the loose debris left from the cutting operation. After soaking, the tube then is ultrasonically cleaned in the heated HCL for 1 to 4 minutes, depending upon the wall thickness. To prevent cracking or breaking of the struts attached to the material left at the two ends of the stent pattern, as a result of harmonic oscillations induced by the ultrasonic cleaner, a mandrel is placed down the center of the tube during the cleaning and scrap removal process. At completion of this process, the stent structures are rinsed in water. They are now ready for electropolishing.

The stents preferably are electrochemically polished, in an acidic aqueous solution such as a solution marketed under the tradename ELECTRO-GLO #300 by the ELECTRO-GLO Co., Inc. in Chicago, Illinois, which is a mixture of sulfuric acid, carboxylic acids, phosphates, corrosion inhibitors and a biodegradable surface active agent. The bath temperature is maintained at about 43.3 to 57.2°C (110 to 135°F) and the current density is about 0.4 to about 1.5 amps/in.<sup>2</sup>. Cathode to anode area should be at least about two to one. The stents further may be treated if desired, for example by applying a biocompatible coating.

Referring now more particularly to FIGS. 11 and 12, it will be apparent that both focused laser spot size and depth of focus can be controlled by selecting beam diameter (FIG. 11) and focal length for the focusing lens (FIG. 12). It will be apparent from FIGS. 11 and 12 that increasing laser beam diameter, or reducing lens focal length, reduces spot size at the expense of depth of field.

Direct laser cutting produces edges which are essentially perpendicular to the axis of the laser cutting beam, in contrast with chemical etching and similar processes which produce pattern edges that are angled. Hence, the laser cutting process of the present invention essentially provides stent cross-sections, from cut-to-cut, which are square or rectangular rather than trapezoidal; see FIG. 5a. The resulting stent structure provides superior performance.

It will be apparent from the foregoing that the described system provides a new and improved method and apparatus for direct laser cutting of metal stents enabling greater precision, reliability, structural integrity and overall quality, without burrs, slag or other imperfections which might otherwise hamper stent integrity and performance. While the invention has been illustrated and described herein in terms of its use as an intravascular stent, it will be apparent to those skilled in the art that the stent can be used in other instances such as to expand prostatic urethras in cases of prostate hyperplasia. Other modifications and improvements may be made without departing from the scope of the invention.

It will be apparent from the foregoing that, while particular forms of the invention have been illustrated and described, various modifications can be made without departing from the scope of the invention. Accordingly, it is not intended that the invention be limited, except as by the appended claims.

APPENDIX A

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5  G69 152C6040.QSY
   G69 CUTS 1 STENT
   G69 UNEVEN U DES. W/END CONFIGS.
   G69 0.0048 BAR WIDTH-.060 DIA.
   G69 9/12/94
   G69 PROGRAM 11 DISK 70
10  G69 CYCLE TIME = 20 MIN.20 SEC

   V1=6 G69 LINEAR CUT
   V2=30 G69 ROTARY+LIN. CUT
   V3=25 G69 R+L FR CUT (FINGER ENDS)
   V4=50 G69 ROTARY CUT
15  V5=500 G69 ROTARY INDEX
   V6=10 G69 SHORT STRAIGHT CUT
   V7=15 G69 LONG SLANT
   V8=20
   G66 Z55 1
   G59 Z.006
20  G68 Z-1 (MIRROR IMAGE Z AXIS)
   M108
   G90 X0 Y0 Z0P300
   M0

25  G69 PROGRAM BODY

   G91X.15 F200
   KN5000 G69 CALL .015" HOLES
   F""000 G69 CALL CROSS HAIR

30  G90 Z-60 F300 G69 START PATTERN
   KN1000 G69 CALL FIRST PATTERN
   G90 Z-180 F300
   KN1000
   G90 Z-300 F300
   KN1000
35  G91 X.042

   M1234
   G90 Z0 F300
   KN2200 R5 G69 MAIN PATTERN
   KN3300 G69 ADDITIONAL PATTERN
40  G90 Z-37.8 F300
   G91 X.0512

   KN3000 G69 CALLS END PATTERN
   G90 Z-157.8 F300
45  KN3000
   G90 Z-277.8 F300
   KN3000
   G90 X1.2888 F200
   G91 M109
   Z360 M108 FV4
50

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5	390 X0 F200 3 M109 3-.60 M108 FV4 390 X0 Y2.5 F300 40 42	
10	N2200 390 Z0 FV5 KN2000 390 Z-120 FV5 KN2000 390 Z-240 FV5 KN2000	G69 MAIN PATTERN
15	391 X.0492 F50 390 Z-300 FV5 KN2000 390 Z-180 FV5 KN2000 390 Z-60 FV5 KN2000 391 X.0492 F50	
20	M6	
25		
30	N3300 G90 Z0 FV5 I 300 G90 Z-120 FV5 KN2000 G90 Z-240 FV5 KN2000	G69 ADDITIONAL PATTERN
35	M6	
40	N4000 G91 M109 FV1 X.01 M108 X-.005 Y.005 M109 Y-.01 M108 X.05 Y.005 F100 M6	G69 CROSS HAIR SUB
45		
50	N5000 M109 X.0075 F3 G3I-.0075 J0 M108 X-.0075 F200 G91 Z180 F300 M109 X.0075 F3 G3I-.0075J0M108	G69 HOLES
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(-0075 Z-180 F500  
 ( F200  
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V1000 G69 FIRST PATTERN  
 391 M109

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V1001 G9X.028937 Z0 FV1  
 V1002 X.000780 Z-0.802141 FV2  
 V1003 X.001255 Z-4.663876  
 V1004 X.001866 Z-4.209330  
 V1005 X.002307 Z-3.239121  
 V1006 X.002646 Z-2.005352  
 V1007 X.002782 Z-0.511842 FV6  
 V1008 X.019383 Z0.000000 FV1  
 V1009 X.001651 Z0.511842 FV3  
 V1010 X.001187 Z0.647442  
 V1011 X.002137 Z1.944237  
 V1012 X.002171 Z1.684496 FV6  
 V1013 X.002510 Z0.324676  
 V1014 X.002476 Z-1.166924  
 V1015 X.002137 Z-2.526744 FV2  
 V1016 X.001459 Z-3.628733  
 V1017 X.000814 Z-4.276175  
 V1018 X.000034 Z-2.916355  
 V1019 X-.000678 Z-3.304057  
 V1020 X-.000882 Z-1.749431  
 V1021 X-.002001 Z-1.359820 FV6  
 V1022 X-.001764 Z0.129870  
 V1023 X-.001866 Z1.166924  
 V1024 X-.001560 Z1.424755 FV3  
 V1025 X-.002001 Z0.972118  
 V1026 X-.001852 Z0.242552  
 V1027 X-.019467 Z0.000000 FV1  
 V1028 X-.002462 Z-0.630254 FV3  
 V1029 X-.002341 Z-1.684496

X-.011 Z3  
 X.011 Z-3

N1030 X-.002103 Z-2.979381 FV2  
 N1031 X-.001730 Z-3.951499  
 N1032 X-.001255 Z-4.535916  
 N1033 X-.000432 Z-4.919798  
 N1034 X.000509 Z-4.923617  
 N1035 X.001195 Z-4.06609  
 N1036 X-.001195 Z-4.06609  
 N1037 X-.000509 Z-4.923617  
 N1038 X.000432 Z-4.919798  
 N1039 X.001255 Z-4.535916  
 N1040 X.001730 Z-3.951499  
 N1041 X.002103 Z-2.979381

X-011 Z-3  
X .1 Z3

5	N1042 X.002341 Z-1.684496	FV3
	N1043 X.002462 Z-0.630254	
	N1044 X.019467 Z0	FV1
	N1045 X.001852 Z0.242552	FV3
10	N1046 X.002001 Z0.972118	
	N1047 X.001560 Z1.424755	
	N1048 X.001866 Z1.166924	FV6
	N1049 X.001764 Z0.129870	
	N1050 X.002001 Z-1.35982	
15	N1051 X.000882 Z-1.749431	FV2
	N1052 X.000678 Z-3.304057	
	N1053 X-.000034 Z-2.916355	
	N1054 X-.000814 Z-4.276175	
	N1055 X-.001459 Z-3.628733	
20	N1056 X-.002137 Z-2.526744	
	N1057 X-.002476 Z-1.166924	FV6
	N1058 X-.002510 Z0.324676	
	N1059 X-.002171 Z1.684496	
	N1060 X-.002137 Z1.944237	FV3
25	N1061 X-.001187 Z0.647442	
	N1062 X-.001651 Z0.511842	
	N1063 X-.019383 Z0	FV1
	N1064 X-.002782 Z-0.511842	FV6
	N1065 X-.002646 Z-2.005352	FV2
30	N1066 X-.002307 Z-3.239121	
	N1067 X-.001866 Z-4.20933	
	N1068 X-.001255 Z-4.663876	
	N1069 X-.000780 Z-0.802141	
35	N1070 X-.028937 Z0	FV1

## G69 RETURN TRIP

	N1071 X-.004643 Z0.324676	FV6
	N1072 X-.002980 Z1.058062	
40	N1073 X-.002772 Z2.513375	FV2
	N1074 X-.002425 Z3.307876	
	N1075 X-.001940 Z4.763189	
	N1076 X-.000693 Z11.37703	
	N1077 X.002841 Z9.921719	
45	N1078 X.005405 Z2.513375	FV6
	N1079 X.005682 Z-2.513375	
	N1080 X.023615 Z-21.95383	FV2
	N1081 X.006375 Z14.74984	
50	N1082 X-.005026 Z13.11118	
	N1083 X-.001951 Z15.82891	
	N1084 X.001951 Z15.82891	
	N1085 X.005026 Z13.11118	
	N1086 X-.006375 Z14.74984	
55	N1087 X-.023615 Z-21.95383	

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V1088 X-.005682 Z-2.513375 FV6  
 V 19 X-.005405 Z2.513375  
 V1090 X-.002841 Z9.921719 FV2  
 V1091 X.000693 Z11.37703  
 V1092 X.001940 Z4.763189  
 V1093 X.002425 Z3.307876  
 V1094 X.002772 Z2.513375  
 V1095 X.002980 Z1.058062 FV6  
 V1096 X.004643 Z0.324676 G0 M108  
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## N2000 G69 MAIN PATTERN

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M109

N1 G9X.036364 Z0 FV1  
 N2 X.000780 Z-0.802141 FV2  
 N3 X.001255 Z-4.663876  
 N4 X.001866 Z-4.209330

X-.0034 Z-3

X.0034 Z3

N5 X.002307 Z-3.239121  
 N6 X.002646 Z-2.005352  
 N7 X.002782 Z-0.511842 FV6  
 N8 X.019383 Z0 FV1  
 N9 X.001651 Z0.511842 FV6  
 N10 X.001187 Z0.647442  
 N11 X.002137 Z1.944237  
 N12 X.002171 Z1.684496  
 N13 X.002510 Z0.324676  
 N14 X.002476 Z-1.166924  
 N15 X.002137 Z-2.526744 FV2  
 N16 X.001459 Z-3.628733  
 N17 X.000814 Z-4.276175  
 N18 X.000034 Z-2.916355  
 N19 X-.000678 Z-3.304057  
 N20 X-.000882 Z-1.749431  
 N21 X-.002001 Z-1.359820 FV6  
 N22 X-.001764 Z0.129870  
 N23 X-.001866 Z1.166924  
 N24 X-.001560 Z1.424755  
 N25 X-.002001 Z0.972118  
 N26 X-.001852 Z0.242552  
 N27 X-.019467 Z0.000000 FV1  
 N28 X-.002462 Z-0.630254 FV6  
 N29 X-.002341 Z-1.684496 FV2  
 N30 X-.002103 Z-2.979381  
 N31 X-.001730 Z-3.951499

X-.004Z3

Z-004Z-3

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N32 X-.001255 Z-4.535916  
 N33 X-.000432 Z-4.919798  
 N34 X.000509 Z-4.923617  
 N35 X.001195 Z-4.06609  
 N36 X-.001195 Z-4.06609  
 N37 X-.000509 Z-4.923617  
 N38 X.000432 Z-4.919798  
 N39 X.001255 Z-4.535916

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X-.004 Z-3  
 X.004 Z3

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N40 X.001730 Z-3.951499  
 N41 X.002103 Z-2.979381  
 N42 X.002341 Z-1.684496  
 N43 X.002462 Z-0.630254 FV6  
 N44 X.019467 Z0 FV1  
 N45 X.001852 Z0.242552 FV6  
 N46 X.002001 Z0.972118  
 N47 X.001560 Z1.424755  
 N48 X.001866 Z1.166924  
 N49 X.001764 Z0.129870  
 N50 X.002001 Z-1.35982  
 N51 X.000882 Z-1.749431 FV2  
 N52 X.000678 Z-3.304057  
 N53 X-.000034 Z-2.916355  
 N54 X-.000814 Z-4.276175  
 N55 X-.001459 Z-3.628733  
 N56 X-.002137 Z-2.526744  
 N57 X-.002476 Z-1.166924 FV6  
 N58 X-.002510 Z0.324676  
 N59 X-.002171 Z1.684496  
 N60 X-.002137 Z1.944237  
 N61 X-.001187 Z0.647442  
 N62 X-.001651 Z0.511842  
 N63 X-.019383 Z0 FV1  
 N64 X-.002782 Z-0.511842 FV6  
 N65 X-.002646 Z-2.005352 FV2  
 N66 X-.002307 Z-3.239121

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X-.0034 Z3  
 X.0034 Z-3

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N67 X-.001866 Z-4.20933  
 N68 X-.001255 Z-4.663876  
 N69 X-.000780 Z-0.902141  
 N70 X-.036364 Z0 FV1

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N69 RETURN TRIP

EP 0714 641 A2

	N73 X-.000508 Z0.475555	FV3
	N74 X-.000882 Z1.294885	
5	N75 X-.000333 Z2.196338	
	N76 X.000084 Z1.75898	
	N77 X.000469 Z1.694045	
	N78 X.000703 Z1.822006	
	N79 X.001038 Z1.566085	
10	N80 X.001424 Z0.926282	
	N81 X.020432 Z0	FV1
	N82 X.001965 Z-0.765854	FV6
	N83 X.002137 Z-1.879302	
	N84 X.002510 Z-1.101989	
15	N85 X.002442 Z-0.194806	
	N86 X.002374 Z0.907183	
	N87 X.002239 Z2.202068	FV2
	N88 X.002001 Z3.239121	
	N89 X.001560 Z4.728812	
20	N90 X.000746 Z5.246384	
	N91 X-.000170 Z5.635995	
	N92 X-.000916 Z5.443099	
	N93 X-.001391 Z4.665786	
	N94 X-.001823 Z3.884654	
25	N95 X-.002375 Z3.109251	
	N96 X-.002714 Z2.267003	
	N97 X-.002680 Z0.907183	FV6
	N98 X-.002884 Z-0.064935	
	N99 X-.002714 Z-1.165014	
30	N100 X-.002273 Z-2.007262	FV3
	N101 X-.001798 Z-1.489690	
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	N103 X-.018795 Z0.000000	FV1
35	N104 X-.001766 Z0.655082	FV2
	N105 X-.001391 Z1.489690	
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	N107 X-.000950 Z3.498862	
	N108 X-.000101 Z2.188699	
40	N109 X.000101 Z2.188699	
	N110 X.000950 Z3.498862	
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	N112 X.001391 Z1.489690	
	N113 X.001766 Z0.655082	
45	N114 X.018795 Z0.000000	FV1
	N115 X.001081 Z-0.529031	FV3
	N116 X.001798 Z-1.489690	
	N117 X.002273 Z-2.007262	
	N118 X.002714 Z-1.165014	FV6
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	N120 X.002680 Z0.907183	
	N121 X.002714 Z2.267003	FV2
	N122 X.002375 Z3.109251	
55	N123 X.001823 Z3.884654	
	N124 X.001391 Z4.665786	

N123 X.000916 Z5.443099  
 N124 X.000170 Z5.635995  
 N125 X-.000746 Z5.246384  
 N126 X-.001560 Z4.728812  
 N127 X-.002001 Z3.239121  
 N128 X-.002239 Z2.202068  
 N129 X-.002374 Z0.907183 FV6  
 N130 X-.002442 Z-0.194806  
 N131 X-.002510 Z-1.101989  
 N132 X-.002137 Z-1.879302  
 N133 X-.001965 Z-0.765854  
 N134 X-.020432 Z0.000000 FV1  
 N135 X-.001424 Z0.926282 FV3  
 N136 X-.001038 Z1.566085  
 N137 X-.000703 Z1.822006  
 N138 X-.000469 Z1.694045  
 N139 X-.000084 Z1.75898  
 N140 X.000333 Z2.196338  
 N141 X.000882 Z1.294885  
 N142 X.000508 Z0.475555 M108 G0  
 M6

N3000 G69 END PATTERN  
 G91M109  
 N2001 G9X.020432 Z 0 FV1  
 N2002 X.001965 Z-.7659 FV8  
 N2003 X.002137 Z-1.8793  
 N2004 X.002510 Z-1.1020 FV6  
 N2005 X.002442 Z-.1948  
 N2006 X.002374 Z.9072  
 N2007 X.002239 Z 2.2021 FV8  
 N2008 X.002001 Z 3.2391  
 N2009 X.001560 Z 4.7288  
 N2010 X.035000 Z 0 FV1  
 N2011 X.005068 Z-1.6024 FV3  
 N2012 X.002576 Z-4.1024  
 N2013 X.001288 Z-6.5623  
 N2014 X-.000572 Z-5.4698  
 N2015 X-.003148 Z-8.4760  
 N2016 X-.005438 Z-6.0161  
 N2017 X-.008014 Z-2.1868  
 N2018 X-.019320 Z 10.1184 FV7  
 N2019 X-.003148 Z-8.7510

X-.008 Z-4 ——— Z-7  
 X.008 Z4 ——— Z 7

N2020 X.005152 Z-13.1246 FV2  
 N2021 X0 Z-17.5287  
 N2022 X-.005152 Z-13.1246 FV3

## EP 0 714 641 A2

	X 008 Z4	FV7
	08 Z-4	
5	N2023 X.003148 Z-8.7510	
	N2024 X.019320 Z 10.1184	
	N2025 X.008014 Z-2.1868	
	N2026 X.005438 Z-6.0161	
10	N2027 X.003148 Z-8.4760	
	N2028 X.000572 Z-5.4698	
	N2029 X-.001288 Z-6.5623	
	N2030 X-.002576 Z-4.1024	
	N2031 X-.005068 Z-1.6024	
15	N2032 X-.034424 Z 0	FV1
	N2033 X-.000916 Z 5.4431	FV2
	N2034 X-.001391 Z 4.6658	
	N2035 X-.001823 Z 3.8847	
	N2036 X-.002375 Z 3.1093	
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	N2038 X-.002680 Z.9072	FV6
	N2039 X-.002884 Z-.0649	
	N2040 X-.002714 Z-1.1650	
	N2041 X-.002273 Z-2.0073	FV2
25	N2042 X-.001798 Z-1.4897	
	N2043 X-.001081 Z-.5290	
	N2044 X-.018795 Z0	FV1
	N2045 X-.001766 Z .6551	FV3
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	N2047 X-.001187 Z 2.3969	
	N2048 X-.000950 Z 3.4989	
	N2049 X-.000101 Z 2.1887	
	N2050 X.000101 Z 2.1887	
35	N2051 X.000950 Z 3.4989	
	N2052 X.001187 Z 2.3969	
	N2053 X.001391 Z 1.4897	
	N2054 X.001766 Z.6551	
	N2055 X.018795 Z 0	FV1
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	N2067 X.000170 Z 5.6360	
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	N2069 X-.001560 Z 4.7288	
	N2070 X-.002001 Z 3.2391	
55	N2071 X-.002239 Z 2.2021	



N2072 X-.002374 Z.9072 FV6  
 : 73 X-.002442 Z-.1948  
 N2074 X-.002510 Z-1.1020  
 5 N2075 X-.002137 Z-1.8793 FV2  
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 N2081 X-.000469 Z 1.6940  
 N2082 X-.000084 Z 1.7590  
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 N2084 X.000869 Z 2.7120  
 15 N2085 X.000239 Z 2.2804  
 N2086 X0 Z 4.3086  
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 N2091 X.000469 Z 1.6940  
 N2092 X.000703 Z 1.8220  
 N2093 X.001038 Z 1.5661  
 N2094 X.001424 Z.9263G0  
 25 M108  
 M6  
  
 N2001  
 : F300  
 30 Xu Y2.5 Z0  
 M0

### 35 Claims

1. A longitudinal flexible stent for implanting in a body lumen, comprising:
  - 40 a plurality of cut cylindrical elements which are independently expandable in the radial direction and which are interconnected so as to be generally aligned on a common longitudinal axis, each cylindrical element having a rectangular cross-section from one cut edge to another; and
  - a plurality of connecting elements for interconnecting said cut cylindrical elements, said connecting elements configured to interconnect said cylindrical elements that are adjacent to each other.
- 45 2. The stent of claim 1, wherein said plurality of cut cylindrical elements include a plurality of peaks and valleys having a serpentine pattern.
3. The stent of claim 2, wherein said plurality of peaks and valleys include a plurality of U-shaped members, a plurality of Y-shaped members, and a plurality of W-shaped members, some of said U-shaped, Y-shaped, and W-shaped
  - 50 members being interconnected.
4. The stent of claim 1, wherein at least some of said plurality of cut cylindrical elements tip radially outwardly to form outwardly projecting edges upon radial expansion of said stent.
- 55 5. The stent of claim 1, wherein said cut cylindrical elements are capable of retaining their expanded condition upon the expansion thereof.
6. The stent of claim 1, wherein said stent is formed of stainless steel.

**EP 0 714 641 A2**

7. The stent of claim 1, wherein said stent is formed from a single piece of tubing.
8. A method of making an expandable metal stent, comprising the steps of:
- 5 supporting a metal tube for controlled linear and rotary motion;  
impinging a finely focused laser beam upon the working surface of said metal tube; and  
providing a protective mandrel within said tube to protect the tube wall opposite the tube wall being cut from  
being ablated by said laser beam,  
whereby a precise pattern is cut into said tube to form said stent.
- 10 9. A method as set forth in claim 8, wherein said metal tube is stainless steel.
10. A method as set forth in claim 8, wherein said protective mandrel is stainless steel.
- 15 11. A method as set forth in claim 8, wherein said laser beam is circularly polarized.
12. A method as set forth in claim 11, wherein said circular polarization is accomplished by a quarter wave plate.
13. A method as set forth in claim 8, wherein said laser beam is spatially filtered.
- 20 14. A method as set forth in claim 8, wherein the size of the focused laser beam spot and depth of field is controlled  
by selecting beam diameter.
15. A method as set forth in claim 8, wherein the size of the focused laser beam spot and depth of field is controlled  
25 by selecting focal length of the beam focusing lens.
16. A method as set forth in claim 8, wherein said laser beam passes through a coaxial gas jet adjacent said tube.
17. A method as set forth in claim 16 wherein the gas is oxygen.
- 30 18. A method as set forth in claim 8 and further including the steps of:  
ultrasonically cleaning said stent after it is formed.
19. A method as set forth in either of claims 1 or 18, and further including the step of electropolishing said stent after  
35 it is formed.
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FIG. 1

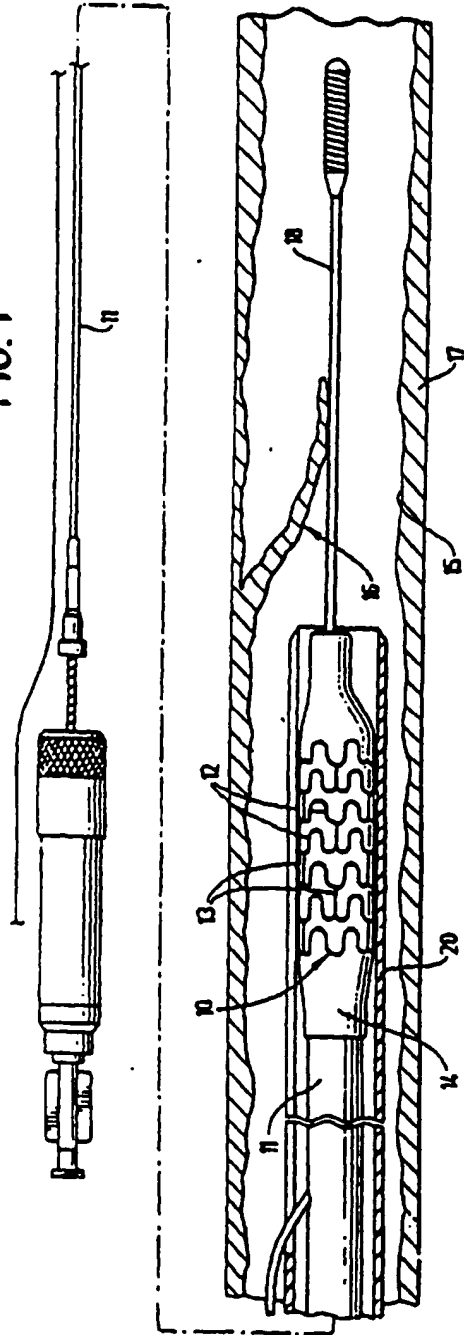


FIG. 3

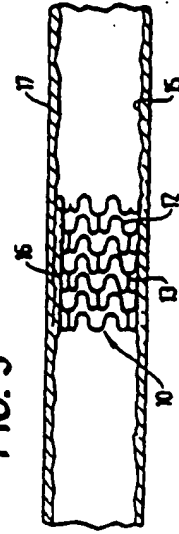
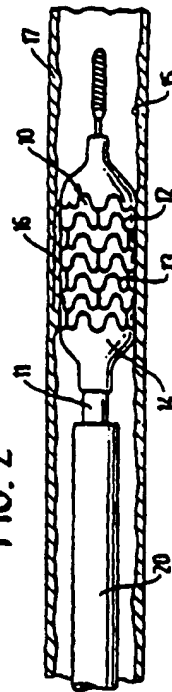
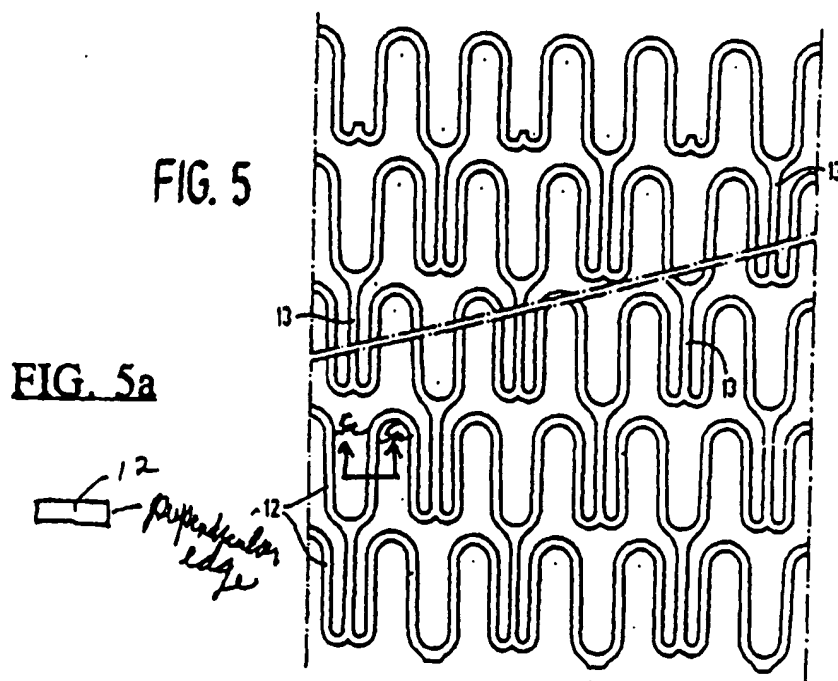
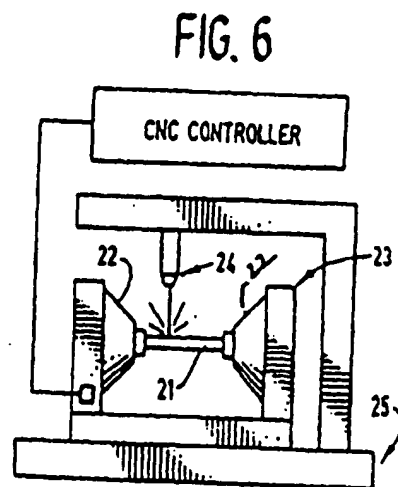
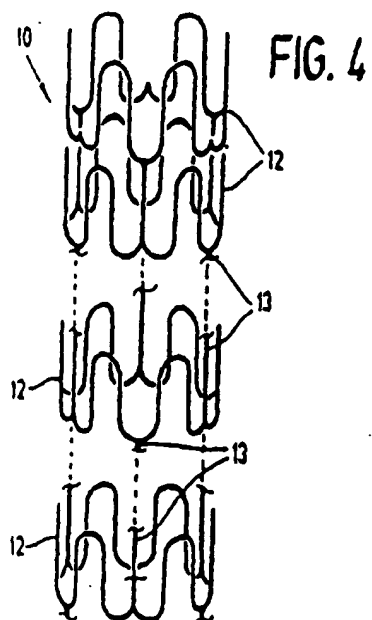


FIG. 2





LASER HEAD, OPTICAL DELIVERY SYSTEM, X,Y, $\theta$  STAGES

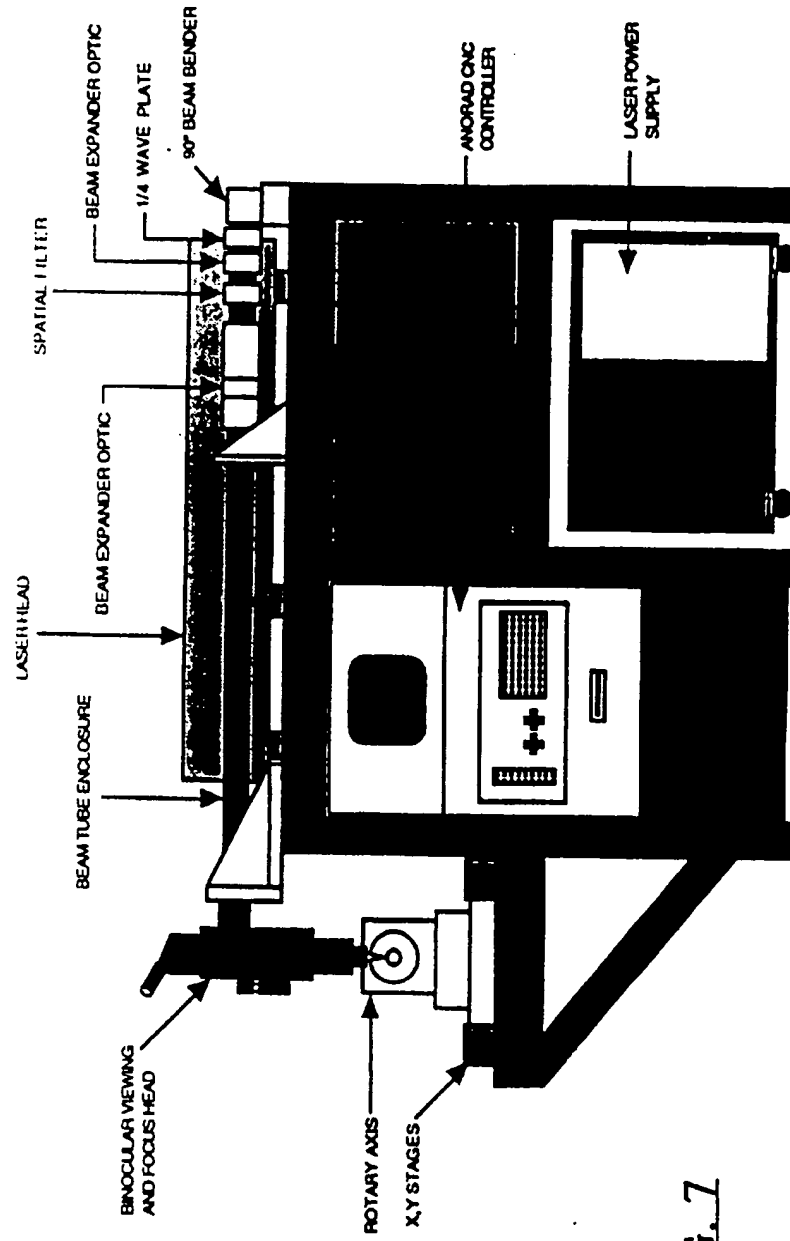
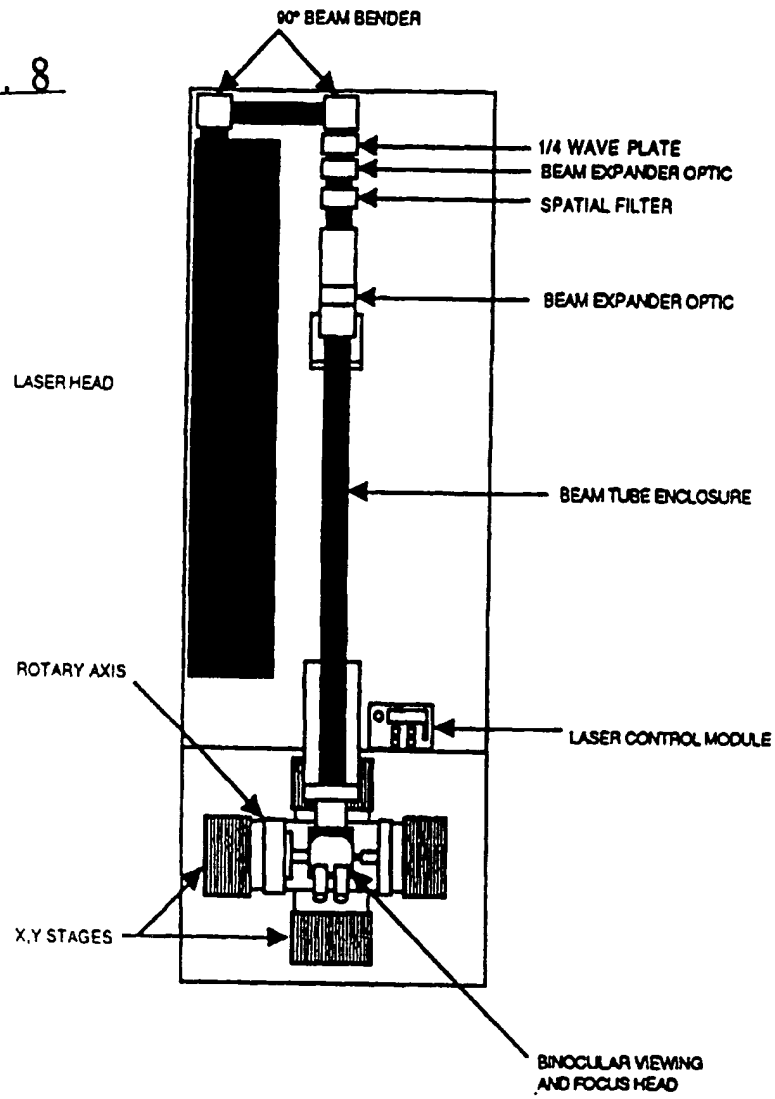


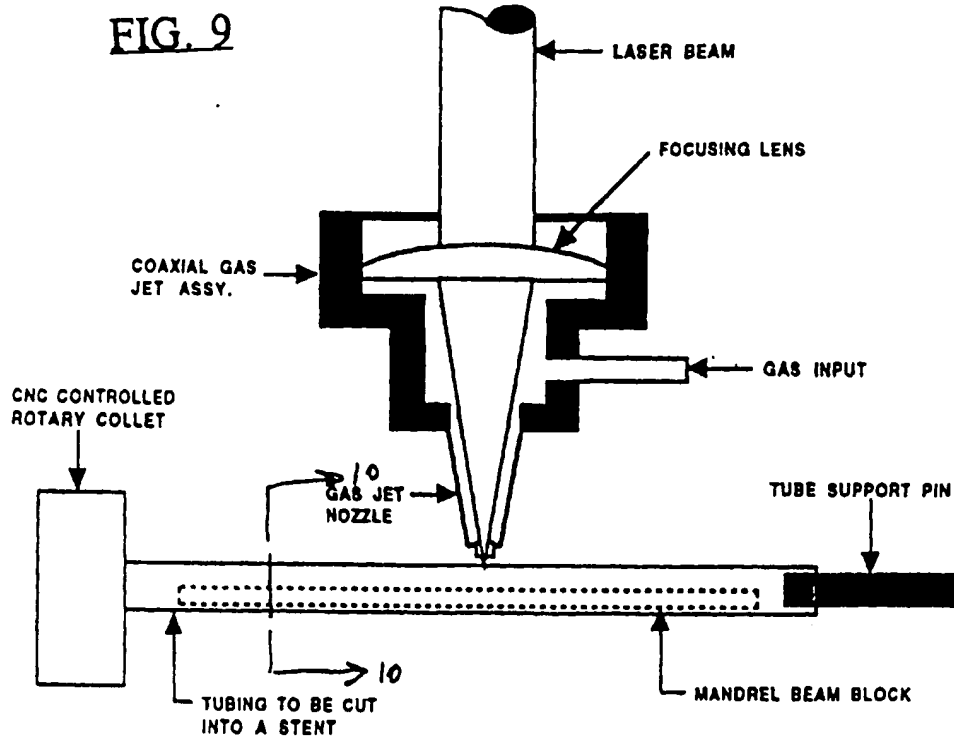
FIG. 7

LASER HEAD, OPTICAL DELIVERY SYSTEM, X,Y, $\theta$  STAGES

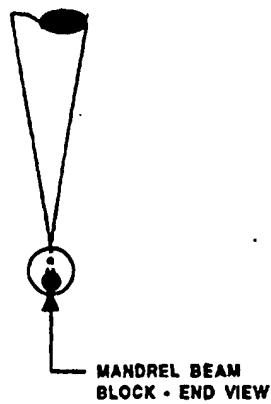
FIG. 8



COAXIAL GAS JET - ROTARY COLLET AND  
TUBE SUPPORT - TUBE BEAM BLOCK

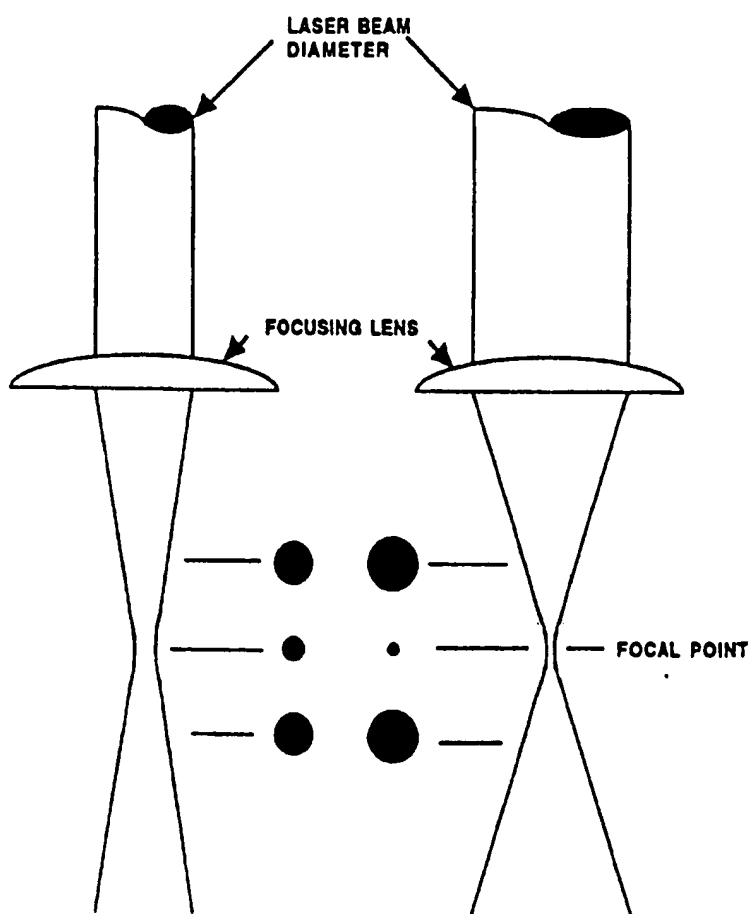


**FIG. 10**



BEAM DIAMETER VS SPOT SIZE AND DEPTH OF FOCUS

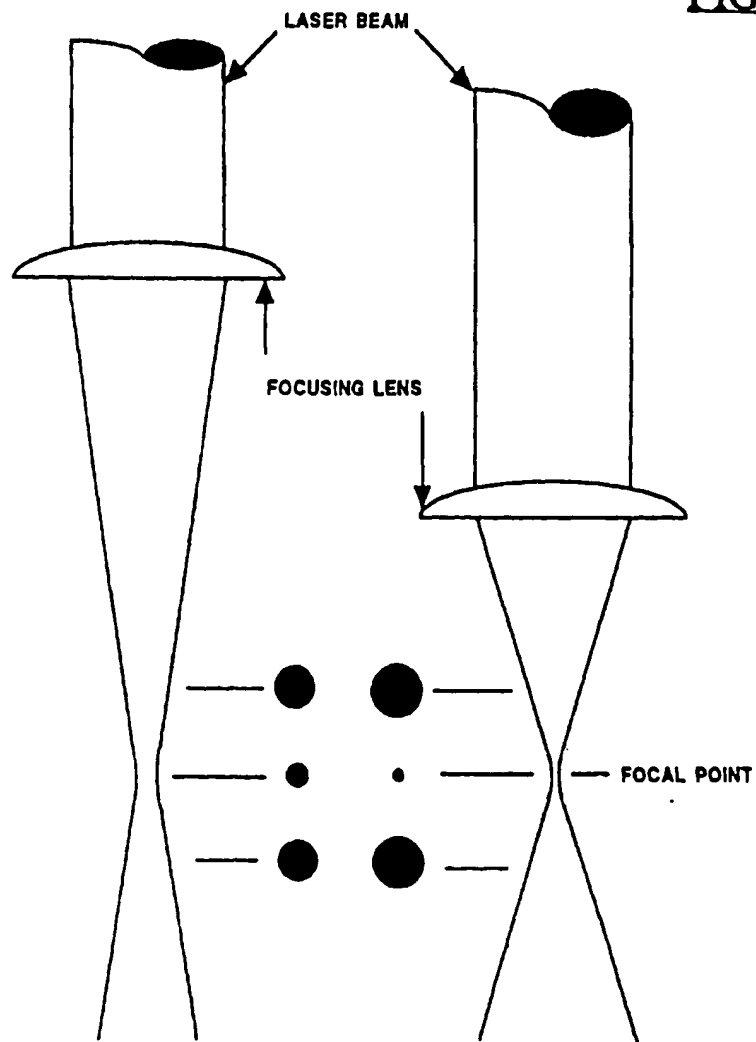
FIG. 11





FOCAL LENGTH VS SPOT SIZE AND DEPTH OF FOCUS

FIG. 12



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